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Physics of Plasmas

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First results of radiation-driven, layered deuterium-tritium (DT) implosions with 3-shock adiabat-shaped drive at the National Ignition Facility

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ABSTRACT

Radiation-driven, layered deuterium-tritium plastic capsule implosions were carried out using a new, 3-shock "adiabat-shaped" drive on the National Ignition Facility. The purpose of adiabat shaping is to use a stronger first shock, reducing hydrodynamic instability growth in the ablator. The shock can decay before reaching the DT fuel, leaving it on a low adiabat and allowing higher fuel compression. The fuel areal density was improved by ~25% with this new drive compared to similar "high-foot" implosions, while neutron yield was improved by more than 4 times, compared to "low-foot" implosions driven at the same compression and implosion velocity.

The goal of inertial confinement fusion (ICF) [1-3] is to implode a spherical target to achieve high compression of the deuterium-tritium (DT) fuel and high temperature in a central hot-spot, to trigger ignition of the DT fuel. During the National Ignition Campaign (NIC) on the National Ignition Facility (NIF) [4], the highest compression of DT fuel was achieved with areal density of ~1.3±0.1 g/cm^2 [4]. These implosions were driven with ~1.6 MJ "low-foot" (LF) laser pulses at peak power of ~325 TW, achieving peak implosion velocities of ~320 km/s [5,6]. While these key performance parameters were close to the goal of the ignition point design [7], the temperatures and neutron yields were significantly lower than expectations from simulations [5,6]. In the lowest-yield implosions, the performance was correlated with the presence of plastic ablator material mixed into the DT hot-spot [8,9]. This can result from hydrodynamic instability growth via the Rayleigh-Taylor (RT) [10,11] and Richtmyer-Meshkov (RM) instabilities [12,13]. In recent x-ray radiography experiments, it was found that these instabilities had larger than expected initial seeds, probably contributing to the poor implosion performance during NIC [14]. The capsule support "tent" also has been found to seed significant instability growth [15], also affecting performance during NIC.

Recent "high-foot" (HF) experiments [16] on NIF have shown much-improved neutron yield performance compared to LF. These HF implosions employed a higher radiation temperature during the early stage (or "the foot") of the drive to launch a stronger first shock into the capsule [17]. This relatively minor modification to the x-ray pulse shape has improved the capsule yield by an order of magnitude and demonstrated the first indications of α-particle self- heating of the DT fuel [18]. The yield improvements were correlated with significantly improved stability at the ablation surface, as measured in the hydrodynamic instability experiments [19,20]. While neutron yield was improved, the fuel compression was reduced in the HF, compared to high-compression LF implosions [16]. The reduced fuel compression was primarily due to the hotter, less compressible main fuel, as caused by the strong first shock.

In addition to larger instability growth at the ablation surface, the LF implosions could also have been affected by low-mode asymmetries, and by stronger instability growth during the deceleration phase as a result of high compression. To understand the role of the ablation-front instabilities in the high-compression implosions, the new "adiabat-shaped" (AS) drives were developed with the x-ray drive [21-23]. The concept of adiabat-shaping was originally developed with direct drive on OMEGA [24-27], using both a decaying shock [24,25] and density gradient relaxation [26] techniques. In the decaying shock concept, a strong shock produced by a laser picket heats the outer region of the ablator, putting it on a higher isentrope. The entropy is often characterized by the adiabat $\alpha = P / P_{cold}$, the ratio of the plasma pressure P to the Fermi pressure of a fully degenerate gas P_{cold} [7]. During acceleration, the higher ablator α leads to higher ablation velocity, which stabilizes the RT instability. When the pre-pulse switches off, the shock is no longer supported and decays as it travels toward the capsule's inner surface, resulting in reduced adiabat in the fuel, allowing high compression [22]. Recently, AS was developed in indirect drive and demonstrated in shock propagation ("key-hole") experiments [23]. In contrast to the direct drive case, this indirect drive AS concept largely operates by optimizing the RM phase, rather than reducing the RT instability growth [21-23].

Adiabat-shaping was developed with 3-shock drives (similar to those used for HF), and with 4-shock drives (similar to LF). In the 3-shock adiabat shaped (3-shk AS) design, the fuel adiabat was reduced slightly (~10%) from nominal α ~2.3 used in the HF [23]. In the 4-shock adiabat shaped design, the fuel adiabat α ~1.6 was similar to that in LF [23]. In this Brief Communication, the first results of hydrodynamic growth and layered DT experiments are presented for the new 3-shock adiabat shaped drive. In these experiments the fuel compression was improved compared to HF implosions, and the neutron yield was improved relative to LF implosions.

Figure 1 shows the laser pulse used in the layered DT implosion with 3-shk AS (shot N150115), compared to the HF drive (shot N130812 [16]) and LF drive (shot N120321 [4]) used in implosions with similar laser powers, energies, and implosion velocities. The pulses for 3-shk AS and LF drives were at a peak power of ~325 TW and total energy of ~1.6 MJ. The pulse for the HF drive used slightly higher power of ~350 TW and laser energy of ~1.7 MJ to compensate for the fact that it was used with a slightly less efficient gold hohlraum, compared to the uranium hohlraum used in the shots with LF and AS drives. We focus here on the shot N150115 with the 3-shk AS drive. Capsule and hohlraum details in this shot were described previously (Refs. [4,16]), with the exceptions that the hohlraum was made of uranium with a 0.6 μm-thick gold lining. The imploding capsule had a plastic ablator with 196-μm wall thickness and 2260-μm-initial outer diameter, within which a 69 μm thick cryogenic DT layer was grown. The thickness of the support membrane (tent) was 33 nm.

As shown in Fig. 1, the HF and 3-shk AS drives have the same high picket (beneficial for instability stabilization at the ablation surface), while the trough was reduced by about a factor of four in the AS drive. As a result, the first shock had less support and decayed while propagating into the shell in the AS drive, reducing the fuel adiabat compared to the HF design [23]. In addition, a slightly lower second pulse also contributed to the lower predicted adiabat of α ~2.1 in the DT fuel with the AS drive, nominally ~10% lower than in the HF [23]. By comparison, the LF drive has a smaller picket and low trough, setting the DT fuel at the low adiabat of α ~1.5 without the benefit of instability stabilization at the ablation surface [23]. Figure 2 shows predicted ablation-front instability growth factors at peak velocity as a function of Legendre mode number for HF, LF, and 3-shk AS drives. Both HF and AS drives have similar instability growth factors, significantly reduced compared to the LF drive.

The instability growth factors were experimentally measured using the Hydrodynamic Growth Radiography (HGR) platform [28,29]. The measured growth factors for the different pulses are compared in Fig. 3. The optical-depth (OD) growth factors were measured at capsule radii of R~650 μm using the drives shown in Fig. 1, except truncated in time to energies of ~1.3 MJ, since the late-time pulse only affects the hydrodynamics after the time of these measurements. All HGR experiments were performed with the same capsules except 2x higher percentage of the Si dopant, in order to increase absorption to the backlighter x-rays to improve experimental sensitivity [28,29]. The measured growth factors at the highest growing modes of 60 and 90 were similar with HF and AS drives, while significantly reduced compared to the LF drive by ~3 and ~5 times, respectively.

Figure 4 shows measured neutron performance results for the AS shot N150115 and compares them with all previous LF and HF implosions. Fuel compression was inferred using the Down-Scattered Ratio (DSR) of scattered neutrons in the energy range from 10 to 12 MeV, relative to primary neutrons in the range from 13 to 15 MeV [30]. The down-scattered neutrons determining DSR are mostly scattered in the DT fuel, and in simulations DSR is proportional to the fuel areal density: $\rho R(g/cm^2) \sim 21 \times DSR$ [30,31]. The measured DSR of ~5.0% (corresponding to the DT fuel areal density of ~1.0 g/cm^2) was increased by ~25% in the AS shot, compared to the similar HF shot N130812 (driven at the same predicted implosion velocity of ~330-340 km/s [16]), which was typical of other HF shots. Even at the higher compression, the measured neutron yield was not degraded compared to the shot N130812. The measured ~25% increase in compression was actually larger than the ~10% increase that was expected to result from the ~10% lower adiabat in the AS design relative to the HF design. As a possible explanation for this unexpectedly large increase in compression, we note that measurements of the hot-electrons were significantly reduced with the AS drive, compared to the HF drive, as measured in shape-tuning experiments with plastic capsules with similar drives to the layered DT implosions [32]. (Hot electrons cannot be reliably measured in the high-yield DT layered implosions.) The number of hot electrons with energy above 170 keV is reduced by a factor of ~10 [32]. This observation suggests a hypothesis that the hot-electron preheat could compromise compression in the HF implosions driven at high power where the hot-electron signals were high.

As evident in Fig. 4, the neutron yield performance in the 3-shk AS shot was improved by about a factor of four, compared to all LF implosions, including those driven at the same implosion velocity, the same capsule thickness, and at the same measured compression with DSR of ~5%. This suggests that the LF implosions were significantly degraded by hydrodynamic instabilities at the ablation front because the growth factors were much higher with LF drives, compared to the AS drive, as shown in Fig. 3. In addition, the thickness of the membrane support (tent) was reduced to 33 nm in the AS shot, compared to 110 nm used in most of the LF experiments. In recent HGR experiments, it was shown that the instability growth of the tent modulation could significantly degrade the capsule integrity during the acceleration phase [14]. The contribution of alpha heating to the total yield was about ~2 times in the AS shot, as shown by a dashed contour in Fig. 4. Such a contribution was similar to highest performing HF shots (see Fig. 4), but at ~10% lower implosion velocity.

In conclusion, the first x-ray driven, layered DT plastic capsule implosion was carried out using a new, 3-shock "adiabat-shaped" drive on the NIF. The adiabat shaping drive was developed in indirect drive to set an outer ablation region on a high adiabat for stabilization of hydrodynamic growth, while keeping the DT fuel on a low adiabat, allowing higher fuel compression. The fuel areal density was improved by ~25% with a new adiabat-shaped drive compared to similar "high-foot" drive, reaching areal density of ~1.0 g/cm^2. The total neutron yield of ~3.8e15 was improved by more than 4 times, compared to "low-foot" implosions driven at the same compression and implosion velocity. The experiments using this new drive will help future studies of the performance degradation due to high-mode instability growth, low-mode shape asymmetries, and hot-electron preheat.

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FIGURE CAPTIONS

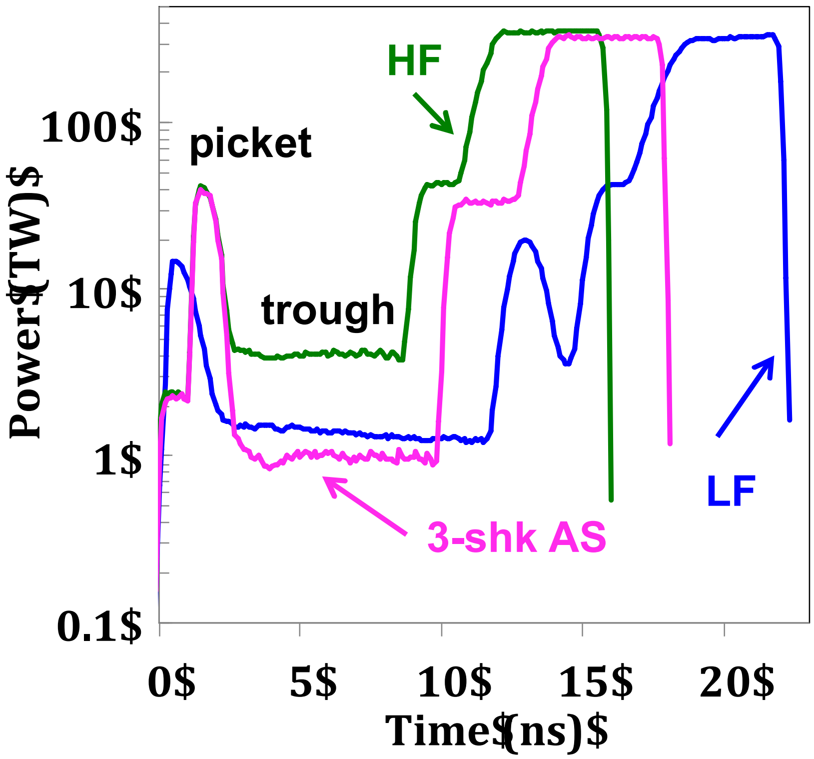
FIG. 1. Examples of the laser power vs time for low-foot (LF), high-foot (HF), and 3-shock adiabat shaped (3-shk AS) drives. Regions of the pickets and trough are indicated.

FIG. 2. Predicted amplitude modulation growth factors as a function of modulation Legendre mode number for low-foot (LF), high-foot (HF), and 3-shock adiabat shaped (3-shk AS) drives at peak velocity.

FIG. 3. Measured (data points) and simulated (solid curves) optical-depth modulation growth factors as a function of modulation mode number for low-foot (LF), high-foot (HF), and 3-shock adiabat shaped (3-shk AS) drives at shell radius of 650 μm from transmission radiograph experiments.

FIG. 4. Measured total DT neutron yield plotted against the ratio of down-scattered 10-12 MeV neutrons over primary 14-17 MeV neutrons (Down Scattered Ratio) for low-foot (LF), high-foot (HF), and 3-shock adiabat-shaped (3-shk AS) drives. Dashed curves represent contours of the calculated yield increase due to alpha heating.

Figure 1



Power(TW)
100$
10$
1$
0.1$
0$
5$
10$
15$
20$
Time(ns)
picket
trough
HF
LF
3-shk AS

Figure 2

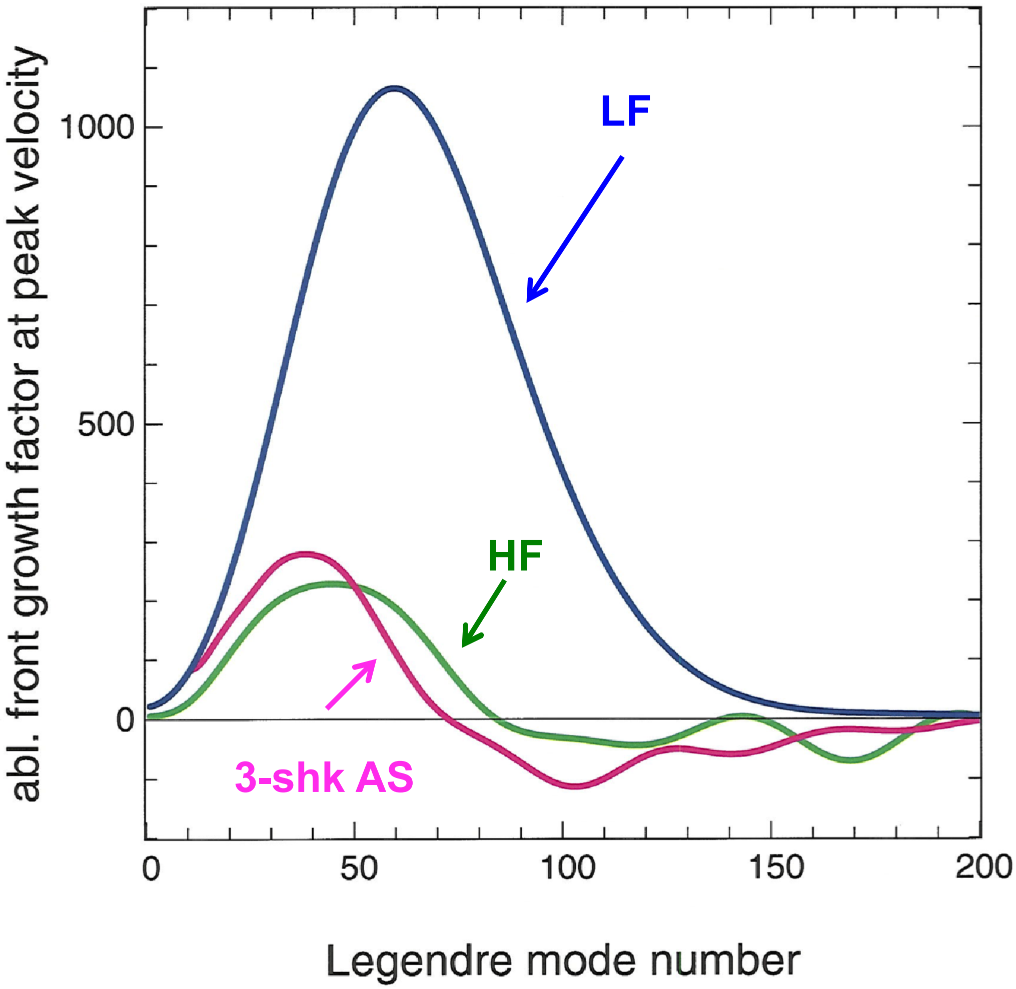
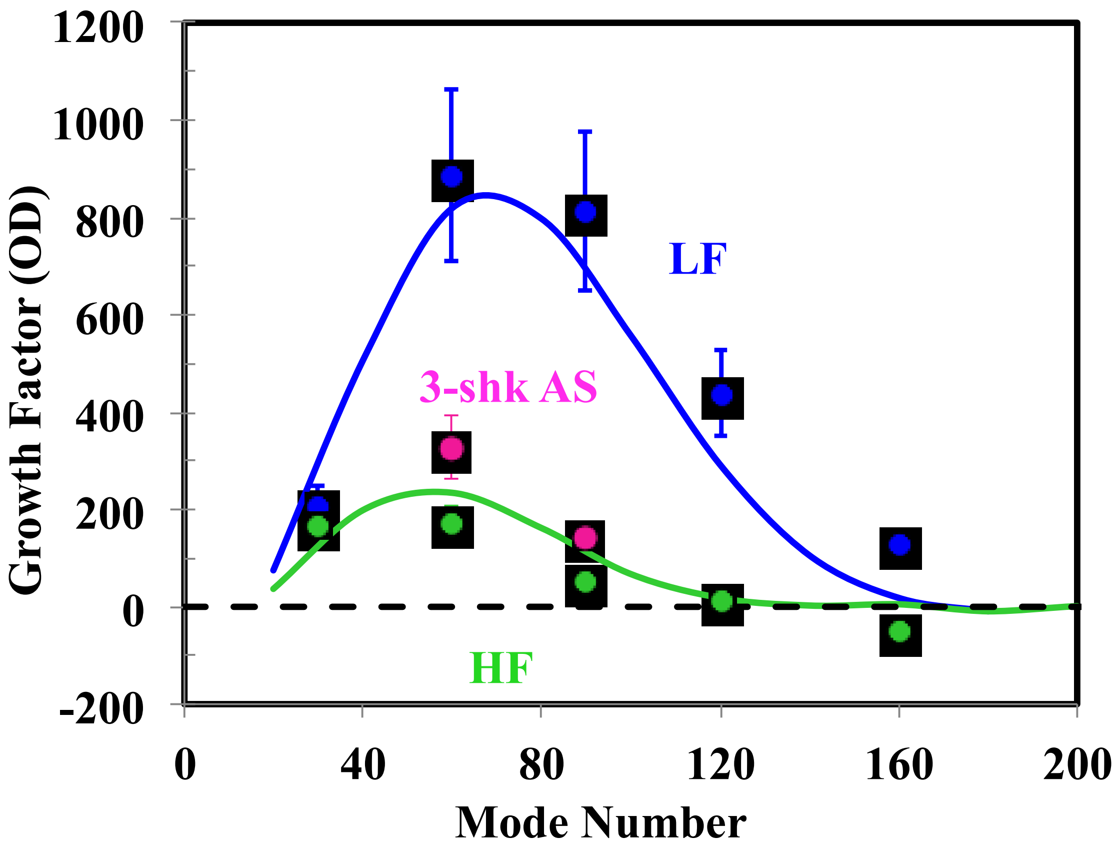
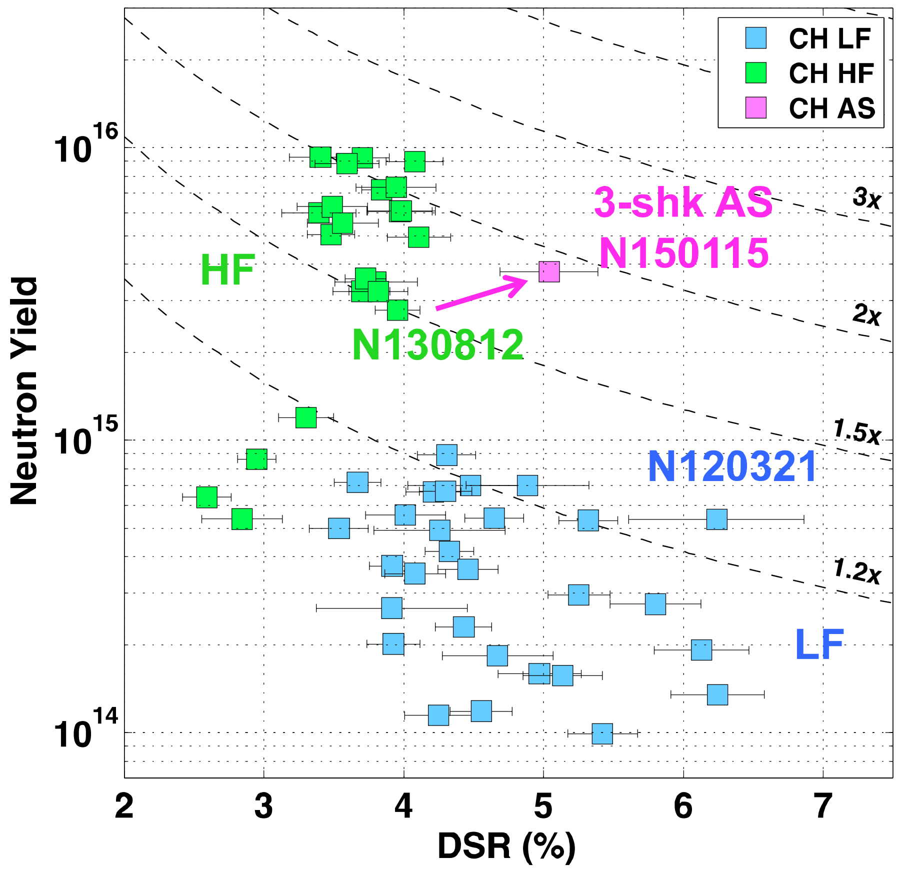

abl. front growth factor at peak velocity
1000
500
0
LF
HF
3-shk AS
0
50
100
150
200
Legendre mode number

Figure 3



1200
1000
800
600
400
200
0
-200
0
40
80
120
160
200
Growth Factor (OD)
Mode Number
LF
3-shk AS
HF

Figure 4


CH LF
CH HF
CH AS
3-shk AS
N150115
HF
N130812
N120321
LF
3x
2x
1.5x
1.2x
Neutron Yield
DSR (%)
10^{16}
10^{15}
10^{14}
2
3
4
5
6
7